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TITLE: GAMMA-RAY AND NEUTRON SPECTROSCOPY OF PLANETARY SURFACES AND ATMOSPHERES.

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GAMMA-RAY AND NEUTRON SPECTROSCOPY OF PLANETARY SURFACES AND ATMOSPHERES*

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ABSTRACT

The neutrons and gamma rays escaping from a planet can be used to map the concentrations of various elements in its surface. In a planet, the high-energy particles in the galactic cosmic rays induce a cascade of particles that includes many neutrons. The γ rays are made by the decay of the naturally-occurring radioelements and by nuclear excitations induced by cosmic-ray particles and their secondaries (especially neutron capture or inelastic scattering reactions). After a short history of planetary γ-ray and neutron spectroscopy, the γ-ray spectrometer and active neutron detection system planned for the Mars Observer Mission are presented. The results of laboratory experiments that simulate the cosmic-ray bombardments of planetary surfaces and the status of the theoretical calculations for the processes that make and transport neutrons and γ rays will be reviewed. Studies of Mars, including its atmosphere, are emphasized, as are new ideas, concepts, and problems that have arisen over the last decade, such as Doppler broadening and peaks from neutron scattering with germanium nuclei in a γ-ray spectrometer.

INTRODUCTION

The energies and intensities of neutrons and γ rays escaping from a planet with very little or no atmosphere can be used to map the concentrations of various elements in the top few tens of centimeters of the surface. In the planet, the high-energy particles in the galactic cosmic rays (GCR) induce a cascade of particles that includes many neutrons.[1] The γ rays are made by the decay of the naturally-occurring radioactive elements (K, U, and Th) and by nuclear excitations induced by cosmic-ray particles.[2,3] The γ rays usually used for chemical mapping are produced by neutron-capture or inelastic-scattering reactions. Certain elements, such as hydrogen, carbon, samarium, and gadolinium, can strongly affect the spectrum of neutrons in a planet, and thus can be sensed indirectly and their concentration-versus-depth profiles determined from neutron spectra[4,5] or γ rays[6,7] from other elements. The Earth's atmosphere is so thick ($\approx$1000 g cm^{-2}) that few cosmic-ray particles reach the surface, and it also prevents γ rays made in the surface from traveling very far. Thus γ-ray spectroscopy on the Earth has been limited to low-flying searches for uranium and studies of the γ rays near the top of the atmosphere. Planetary γ-ray and neutron spectroscopy as considered here refer to objects with no or thin atmospheres, such as the Moon, Mars, asteroids, and comets.

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Planetary γ-ray and neutron spectroscopies were both proposed around 1960 by Arnold,[8] Lingenfelter,[4] and others. However, planetary missions with such instruments have been very rare. On the Apollo 15 and 16 missions in 1971 and 1972, respectively, NaI(Tl) γ-ray spectrometers were flown, and spectra were accumulated over about 20% of the moon's surface. Maps of iron, titanium, magnesium, and natural radioactivity were produced from the Apollo γ-ray data.[9,10] Most existing reports for planetary γ-ray spectroscopy date back to the Apollo era. Future missions will used advanced technologies for both γ-ray and neutron spectroscopy.

High-purity-germanium γ-ray spectrometers are scheduled to be launched in the 1990s on the Mars Observer, which will be in a polar orbit, and probably on Soviet martian orbiters. The Mars Observer Gamma-Ray Spectrometer (GRS) also will include instrumentation that can detect thermal and epithermal neutrons. A γ-ray spectrometer[11] is part of the penetrator that has been tentatively accepted for the proposed Comet Rendezvous Asteroid Flyby mission. The greatly improved detection capabilities (such as the high resolution for γ rays) and new targets (e.g., Mars with its thin atmosphere) have been changing our ideas for planetary spectroscopy considerably since the Apollo days. The Mars Observer GRS with its neutron-detection instrumentation is described below. Also discussed are the results of some simulation experiments and preliminary results for γ-ray and neutron calculations for Mars. The new instruments will produce significantly improved measurements, but they also require additional studies and calculations to anticipate possible complications arising from their greater sensitivities.

GAMMA-RAY AND NEUTRON DETECTION ON THE MARS OBSERVER MISSION

The proposed Mars Observer γ-ray detector will be a high-purity n-type germanium (hpGe) diode with a 56-mm diameter and a 56-mm length. It will be cooled to $\lesssim$100 K by a passive radiator. The hpGe will be surrounded by a plastic scintillator, and the GRS's electronics will reject signals in the hpGe detector that are in coincidence with a signal in the plastic scintillator, eliminating background signals from the passage of charged cosmic rays through the hpGe detector. Signals from the hpGe for energies from $\sim$0.2 to $\sim$10 MeV will be processed in a pulse height analyzer. Below and above $\approx$2.4 MeV, the spectra will have $\approx$0.6 and 1.2 keV per channel, respectively. An entire γ-ray spectrum ($\approx$10,000 channels) will be transmitted every $\sim$20 seconds.

Thermal ($\lesssim$0.1 eV) and epithermal ($\sim$1-1000 eV) neutrons will be detected using a boron-loaded plastic scintillator for the anti-coincidence shield. The $^{10}B(n,\alpha)^{7}Li$ reactions induced by these neutrons in the borated plastic will produce a unique signal in the scintillator's output.[12] Because the spacecraft moves at a velocity slightly faster (3.4 km/s) than that of a thermal neutron, the neutron count rates in each of the four faces of the anti-coincidence shield (which is pyramid shaped and fixed relative to the spacecraft's velocity) can be used as a Doppler filter to determine the fluxes and spectral shapes of thermal and epithermal neutrons.[13]

SIMULATION EXPERIMENTS

Several experiments have been done recently at accelerators to simulate the processes that produce γ rays in a planet's surface, and more are planned by the Mars Observer GRS team. In one series of irradiations, thick targets were bombarded with 6-GeV protons,[14] simulating the cascade of GCR particles in a large solid target. The spectra of γ rays measured in front of thick iron targets showed many narrow lines whose fluxes were in good agreement with theoretical calculations.[14]

As neutrons dominate the production of most γ rays,[2,3] another series of irradiations was done using neutrons from a 14-MeV neutron generator.[15,16] The concrete in the room around the neutron generator moderated many neutrons and produced neutrons with a continuum of energies from 14 MeV to thermal. The γ-ray spectrum from the irradiation of an aluminum target[16] is shown in Fig. 1. The fluxes of γ rays made by the Fe(n,γ) reactions were in good agreement with calculations for thermal neutrons, even though the spectrum of neutrons in the simulation had an epithermal/thermal ratio similar to that in the moon, showing that thermal yields are good for calculating fluxes of neutron-capture-produced γ rays.[15]

Several aspects of the results for the simulations with $\leq$14-MeV neutrons were different from our experience with the low-resolution Apollo γ-ray data. As marked with diagonal lines in the top part of Fig. 1, five peaks with unusual shapes were observed. These peaks are shaped normally at their low-energy sides, and their energies correspond to those for the de-excitation of low-lying levels in germanium isotopes. The high-energy sides of these peaks extend for ~50 keV, and are caused by the summing of the recoil energy from a Ge(n,n′) reaction with the de-excitation γ ray.[15] Except for the peak at and above 834 keV, these sawtooth-shaped peaks in a Ge detector should not interfere with the major γ rays expected from a planetary surface. The high-energy tail above 834 keV will be under the inelastic-scattering peaks from Al and Fe at 844 and 847 keV, respectively. Also marked in Fig. 1 is the peak at 4.438 MeV from the ^{12}C(n,nγ)^{12}C reaction, which has a width of 53 keV compared to the 5-keV width of an adjacent peak from Si. This Doppler broadening of the major carbon inelastic-scattering peak and the low cross section for the ^{12}C(n,γ) reaction will make the detection of carbon in a planetary surface by high-resolution γ-ray spectrometers difficult.

In my 1978 paper on the fluxes of γ rays expected from planetary surfaces,[3] I noted that cross sections for the production of γ rays by nonelastic-scattering reactions were often scarce. Usually the highest neutron energy used in measuring cross sections for the production of nonelastic-scattering γ rays is below 20 MeV, and often some energies have not been measured, such as from $\approx$6-13 or >15 MeV. Few γ-ray-production cross sections have been measured for the proton energies of interest (hundreds of MeV to several GeV). Recently several irradiations have been done with high-energy ($\leq$78 MeV) neutrons[17] and more are planned to measure such cross sections. The lack of good cross sections for nonelastic-scattering reactions limits our ability to calculate the leakage fluxes of such γ rays, especially for those γ rays made by high-energy particles and that interfere with inelastic-scattering γ rays. For example, the production of 1.369-MeV γ rays by the $^{28}Si(n,n\alpha\gamma)^{24}Mg$ reaction could strongly interfere with the signal from the $^{24}Mg(n,n\gamma)^{24}Mg$ reaction that is used to determine magnesium concentrations in a planetary body.[3]

RECENT CALCULATIONS OF MARTIAN NEUTRON AND GAMMA-RAY LEAKAGE FLUXES

In planning for the Mars Observer Gamma-Ray Spectrometer experiment, calculations have recently been done for the production and transport of neutrons[5,18] and γ rays[7] in the martian surface and atmosphere. All of these calculations included a 16-g/cm^2-thick atmosphere (95.7% CO_2, 2.7% N_2, and 1.6% ^{40}Ar) and used the composition of the martian surface soil as determined by the Viking landers. Much of the emphasis in these calculations has been on the highly-variable amounts of volatiles (H_2O and CO_2) that can be present in or on the martian surface. The equilibrium distributions of neutrons in Mars were calculated using the ONEDANT[5,18] and the ANISN[7] neutron-transport codes. The ONEDANT code was modified to include the effects of gravity and the neutron's beta decay.[18] Neutrons that escape Mars with $E \leq 0.132$ eV are gravitationally bound, although some neutrons beta decay before returning to the planet. Neutron-transport calculations done with and without the effects of gravity showed that gravity increased the flux of neutrons at the top of the martian atmosphere by $\approx$29%, but that the neutron-flux increase at the top of the soil due to gravity was only a few percent.[18]

These calculations[5,7,18] indicate that the martian atmosphere and the presence of H_2O in or CO_2 on the martian surface significantly affect the distributions of neutrons. Hydrogen rapidly thermalizes neutrons and shifts their depth distributions towards the surface. Because of its low absorption cross section, CO_2 builds a large reservoir of low-energy neutrons that can leak back into the surface.[5,18] The neutron count rates expected in the GRS's anti-coincidence shield are high enough to allow a rapid determination of the concentrations of H_2O and CO_2 in and on the surface from the observed fluxes and spectral shapes of the thermal and epithermal neutrons.[5] The depth that H_2O is below the surface can often be determined from the neutron[5] and γ-ray[7] data. Both the measured γ-ray and neutron leakage fluxes can be used together to get additional information on the concentration and stratigraphy of H_2O and CO_2 in the top meter of the martian surface.

The fluxes from the ANISN neutron-transport calculations were used to determine the production rates of γ rays by nonelastic-scattering and neutron-capture reactions.[7] The γ rays made by these reactions and by the natural decay of K, Th, U, and their daughters were transported through the martian surface and atmosphere to get fluxes at the spacecraft. The γ rays most suitable for detecting the expected major elements and the radioelements have strong enough leakage fluxes that they should be detectable with integration times of hours to several hundred hours.[19] The determination of these elements should aid in identification of the major rock types present and the degree of local and global refractory enrichment. Readily detectable in γ-ray spectra will be S and Cl, which might be present in surface precipitates or subsurface brines. Besides elemental abundances, the γ-ray data can also be used to study the distribution of hydrogen and CO_2 in Mars by comparing γ rays made by both nonelastic-scattering and neutron-capture reactions with one element.[7]

STUDIES OF THE MARTIAN ATMOSPHERE

The martian atmosphere is very interesting in many ways. Its thickness varies over a martian year by a factor of $\sim$2 as CO_2 frost is deposited and sublimed from the seasonal polar caps. The thickness of the atmosphere also varies with location, being the least over the huge ($\approx$27-km high) volcano Olympus Mons and the greatest above the $\approx$7-km deep canyons of Valles Marineris. These variations in the atmospheric thickness need to be considered in the neutron and γ-ray transport calculations. Nuclear interactions with the constituents of the martian atmosphere also could interfere with the γ-ray spectroscopy of carbon, nitrogen, oxygen, and potassium in the surface. (The first three elements are in both locations, and potassium is assayed using the 1.461-MeV γ ray of ^{40}K, which is from the decay of the first excited level of ^{40}Ar.) Fortunately, most γ rays made by nonelastic-scattering reactions in the low density of the atmosphere should be Doppler broadened[20] and thus shouldn't interfere with the narrow γ-ray lines that are expected from most nonelastic-scattering reactions in the martian surface. A fairly narrow γ-ray line at 6.13 MeV was seen in a high-resolution Ge(Li) spectrometer at the top of the Earth's atmosphere.[21] While much of this line could be from the decay of ^{16}N, it is also possible that it was due to the γ ray at that energy from the $^{16}O(n,n\gamma)^{16}O$ reaction being Doppler-broadened to $\sim$30 keV.[22] Gamma rays made in the atmosphere by the decay of radionuclides (such as ^{16}N and ^{41}Ar) and by neutron-capture reactions (mainly with nitrogen and ^{40}Ar) are not expected to be broadened significantly.

The leakage fluxes of martian neutrons and γ rays also can be used to study the martian atmosphere. The martian atmospheric attenuates the intensities of γ rays from the martian surface,[23] especially for energies below $\sim$1 MeV, and its thickness can be determined from the differences in the attenuation of several γ-ray lines with known relative intensities and very different energies, such as the 239 and 2615-keV γ rays in the thorium chain. As the CO_2 in the martian atmosphere strongly affects the fluxes and spectra of leakage neutrons, the neutron data also can monitor atmospheric thicknesses, possibly even day-to-night variations as a function of season and location.[5] The thickness of the CO_2 deposits at the seasonal polar caps could also be determined as a function of time and location by these techniques. The γ rays made by neutron-capture reactions with ^{40}Ar (e.g., the 1294-keV line from the decay of ^{41}Ar) and nitrogen also could be used to study the martian atmosphere.

SUMMARY

Future planetary missions to the terrestrial planets and to small bodies (comets and asteroids) will have as one of their major objectives the determination of their chemical compositions. Gamma-ray and neutron spectroscopies are excellent methods for orbital or in-situ chemical studies of these objects. Such instruments are scheduled to fly on the Mars Observer Mission and have been tentatively accepted for comet penetrators. Our ideas for these missions have changed considerably since the days of the Apollo missions with their NaI(Tl) γ-ray spectrometers. New detectors (e.g., high-purity germanium) and techniques (Doppler-filter neutron spectroscopy) are available, and the new targets are different in many ways from the moon (atmospheres and volatiles). As discussed above, much work, including simulation experiments and theoretical calculations, is being done in planning for upcoming missions.

Several problems have been identified with these future γ-ray spectroscopy experiments. The hpGe detectors can be fairly easily damaged by cosmic radiation. Experiments to understand how and when such radiation damage occurs are being done with the goal of minimizing such effects. The high resolution of hpGe γ-ray spectrometers increases our ability to measure concentrations of most elements but means that we must be careful of effects such as Doppler broadening and interferences to major γ-ray lines from other sources. The laboratory simulations and theoretical calculations are important, especially now that we will be going to objects for which we have no "ground truth" to normalize our measurements.

The data obtained from both the γ-ray and neutron modes of the Mars Observer GRS will complement each other, and their use together will considerably improve the scientific return. For example, the elemental results from the γ-ray spectra are needed to help interpret the transport of the leakage neutrons. As neutrons are the major source of most γ rays, direct measurement of the neutron leakage flux can aid in interpreting the γ-ray data. The measured neutron and γ-ray fluxes also can help to infer the presence of certain elements not directly observed in the γ-ray spectra, such as relatively high amounts of neutron-absorbing gadolinium and samarium. The intensity of the leakage thermal neutrons can be used with the fluxes for the neutron-capture γ rays from hydrogen (ratioed to those from Si or Fe) to determine the concentration and stratigraphy of H_2O in the top $\sim$100 g cm^{-2} of the martian surface or the thickness of CO_2 above the martian surface. Such studies of volatiles will be very important not only for studies of Mars but also for comets and possibly for asteroids and the polar regions of the moon.

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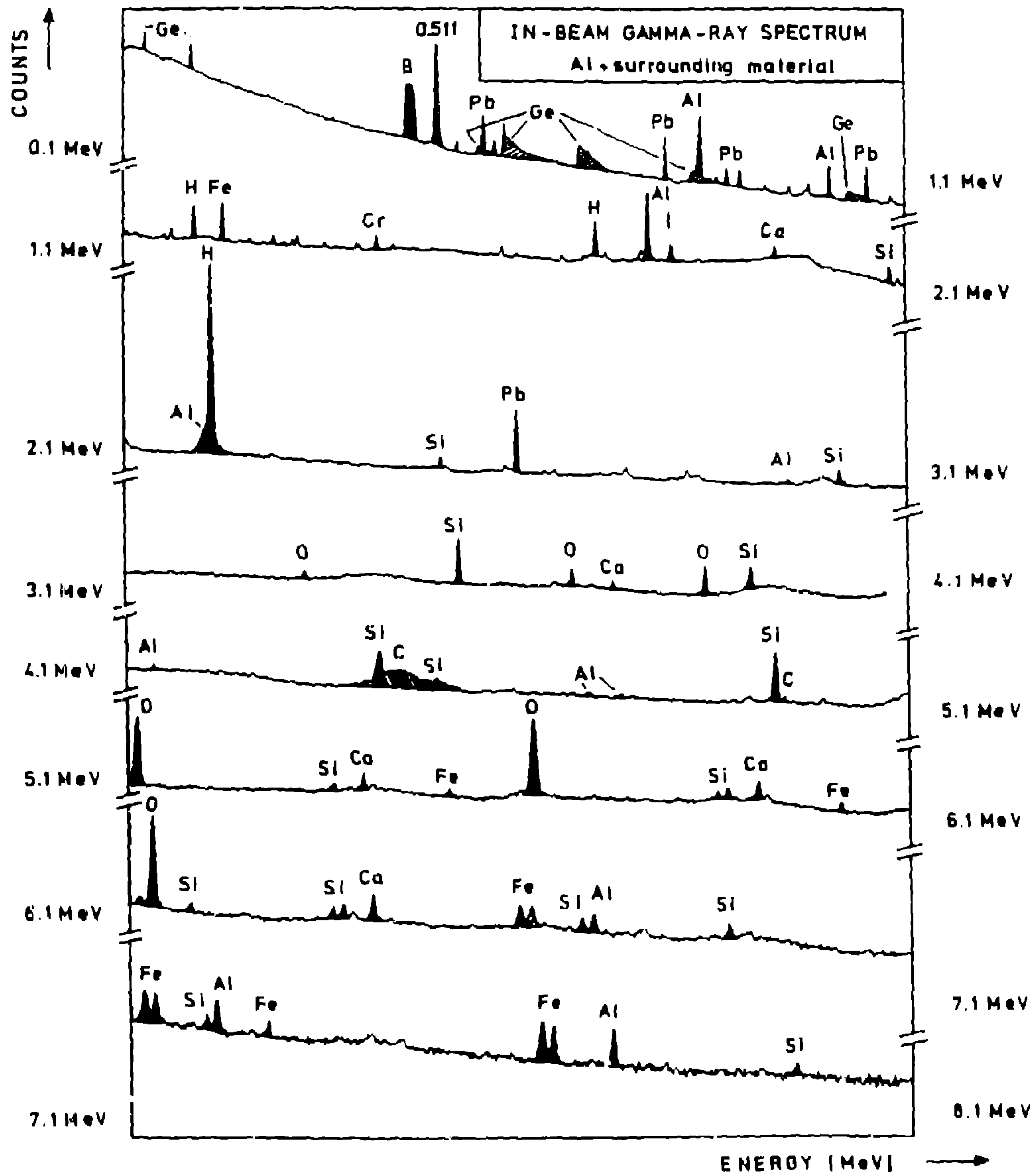

Fig. 1. The γ-ray spectrum observed from aluminum irradiated with 0 to 14-MeV neutrons.[16] Most γ rays were produced in the concrete around the 14-MeV neutron generator and in the material (such as lead and borated paraffin) surrounding the Ge detector. Shaded are the five asymmetric Ge peaks from 596 to 1040 keV and the Doppler-broadened peak at 4.438 MeV from the $^{12}C(n,n\gamma)^{12}C$ reaction.[15]